

Solar models and solar neutrinos: a quantitative analysis of the solar composition problem

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Outline

- The solar composition problem
- A quantitative analysis of the solar composition problem
- CNO neutrinos
- Summary and conclusions

Looking at the solar interior ...

The interior of the Sun can be studied by using **solar neutrinos** and **helioseismology**

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Solar neutrinos:

Experimental results agree with Standard Solar Models (SSM) + flavor oscillations:

	AGSS09	GS98	Obs.	Note that:
Φ_{pp}	$6.03 (1 \pm 0.005)$	$5.98 (1 \pm 0.005)$	$6.05(1^{+0.003}_{-0.011})$	
Φ_{Be}	$4.56 (1 \pm 0.06)$	$5.00 (1 \pm 0.06)$	$4.82(1^{+0.05}_{-0.04})$	
Φ_{B}	$4.59 (1 \pm 0.11)$	$5.58 (1 \pm 0.11)$	$5.00(1 \pm 0.03)$	
Φ_{N}	$2.17 (1 \pm 0.08)$	$2.96 (1 \pm 0.08)$	≤ 6.7	
Φ_{O}	$1.56 (1 \pm 0.10)$	$2.23 (1 \pm 0.10)$	≤ 3.2	$\delta\Phi_{\text{B}} \simeq 20 \delta T_{\text{c}}$

Units: pp: $10^{10} \text{ cm}^2 \text{ s}^{-1}$; Be: $10^9 \text{ cm}^2 \text{ s}^{-1}$; B: $10^6 \text{ cm}^2 \text{ s}^{-1}$; N: $10^8 \text{ cm}^2 \text{ s}^{-1}$; O: $10^8 \text{ cm}^2 \text{ s}^{-1}$;

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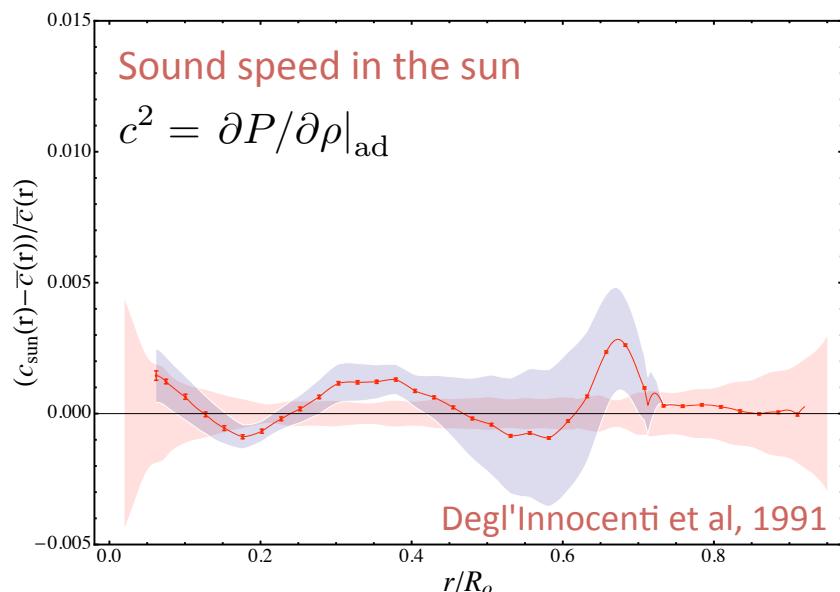
Helioseismology: impressive agreement...

Surface helium abundance

$$Y_b = 0.2485 \pm 0.0034$$

Inner radius of the solar convective envelope

$$R_b/R_\odot = 0.715 \pm 0.001$$



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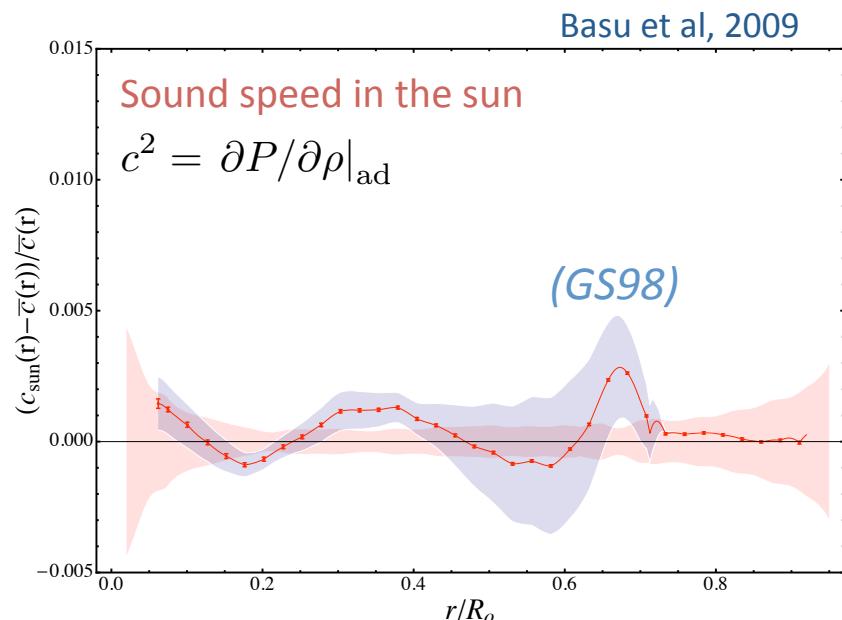
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$$Y_b = 0.245 \quad (\text{GS98})$$

Inner radius of the solar convective envelope

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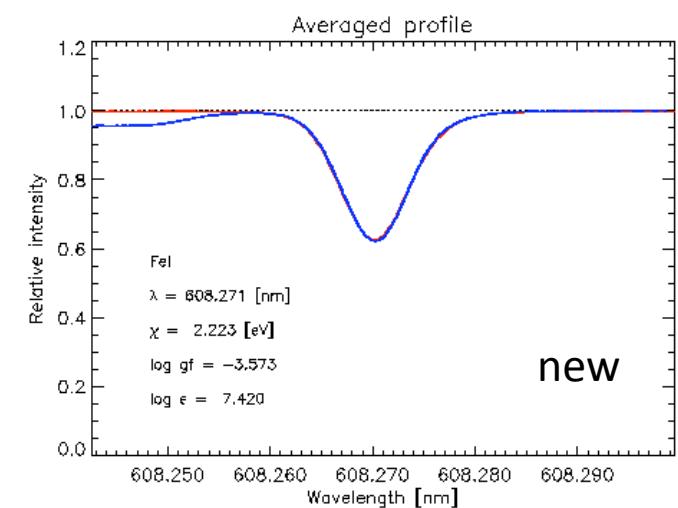
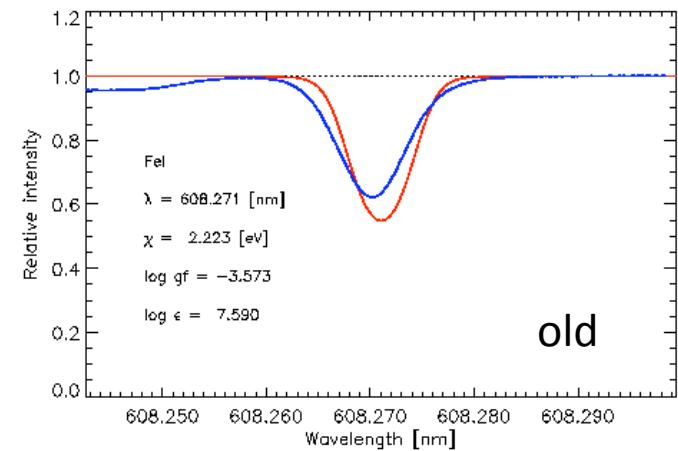
... till few years ago

Asplund et al. 05 (AGS05); Asplund et al. 09 (AGSS09)

Re-determination of the photospheric abundances of nearly all available elements

Improvements with respect to previous analysis^(*):

- 3D model instead of the classical 1D model of the lower solar atmosphere
- Careful and very demanding selection of the spectral lines... AVOID blends!!! NOT TRIVIAL!!!
- Careful choice of the atomic and molecular data NOT TRIVIAL!!!!
- NLTE instead of the classical LTE hypothesis... WHEN POSSIBLE !!!
- Use of ALL indicators (atoms as well as molecules,CNO)



^(*)N. Grevesse talk at PHYSUN10

The solar composition problem

AGS05 and AGSS09

Downward revision of heavy elements
photospheric abundances ...

Element	GS98	AGSS09	δz_i
C	8.52 ± 0.06	8.43 ± 0.05	0.23
N	7.92 ± 0.06	7.83 ± 0.05	0.23
O	8.83 ± 0.06	8.69 ± 0.05	0.38
Ne	8.08 ± 0.06	7.93 ± 0.10	0.41
Mg	7.58 ± 0.01	7.53 ± 0.01	0.12
Si	7.56 ± 0.01	7.51 ± 0.01	0.12
S	7.20 ± 0.06	7.15 ± 0.02	0.12
Fe	7.50 ± 0.01	7.45 ± 0.01	0.12
Z/X	0.0229	0.0178	0.29

$$[I/H] \equiv \log(N_I/N_H) + 12$$

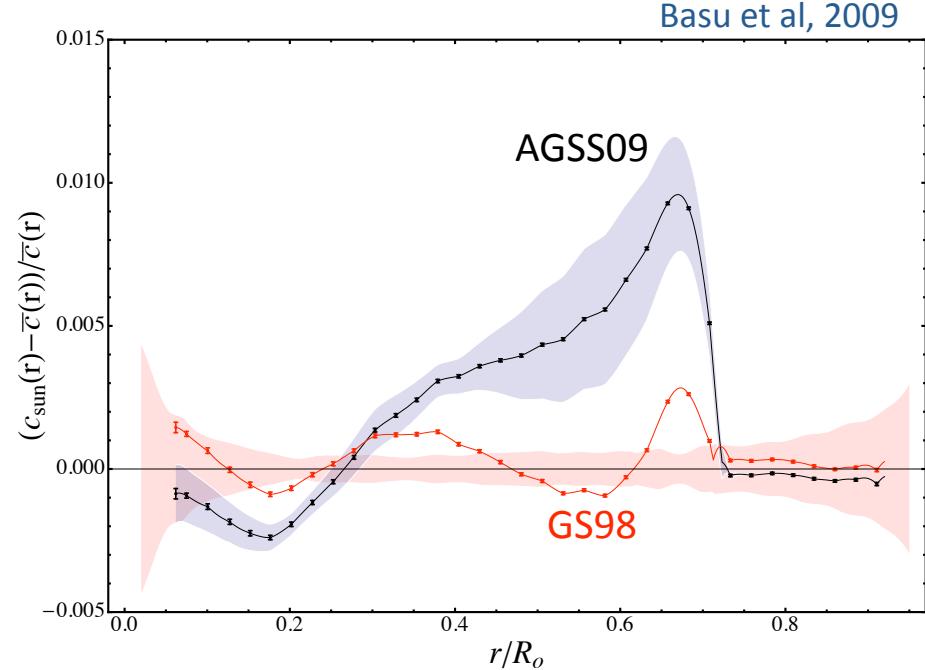
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... leads to SSMs which do not correctly reproduce helioseismic observables

	AGSS09	GS98	Obs.
Y_b	$0.2319(1 \pm 0.013)$	$0.2429(1 \pm 0.013)$	0.2485 ± 0.0035
R_b/R_\odot	$0.7231(1 \pm 0.0033)$	$0.7124(1 \pm 0.0033)$	0.713 ± 0.001
Φ_{pp}	$6.03(1 \pm 0.005)$	$5.98(1 \pm 0.005)$	$6.05(1^{+0.003}_{-0.011})$
Φ_{Be}	$4.56(1 \pm 0.06)$	$5.00(1 \pm 0.06)$	$4.82(1^{+0.05}_{-0.04})$
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($\approx 4\sigma$ discrepancies)

So what ...

Is there something **wrong** or **unaccounted** in solar models?

Is the **chemical evolution** not understood (extra mixing?) or peculiar (accretion?) with respect to other stars?

Are properties of the solar matter (e.g. **opacity**) correctly described?

Is this discrepancy pointing at **new physics** (e.g. WIMPs in the solar core?)

Consider that:

The Sun provide the **benchmark** for stellar evolution. If there is something wrong in solar models, then this is wrong for all the stars ...

A quantitative analysis of the solar composition problem

To combine observational infos, we need an estimator that is **non-biased** and that can be used as a **figure-of-merit** for solar models with different composition:

$$\chi^2 = \min_{\{\xi_I\}} \left[\sum_Q \left(\frac{\delta Q - \sum_I \xi_I C_{Q,I}}{U_Q} \right)^2 + \sum_I \xi_I^2 \right]. \quad \text{Fogli et al. 2002}$$

Where:

$$\delta Q = \frac{Q_{\text{obs}} - Q}{Q}$$

$$\{\delta Q\} = \{\delta\Phi_B, \delta\Phi_{Be}, \delta Y_b, \delta R_b; \delta c_1, \delta c_2, \dots, \delta c_{30}\}$$

$^{7\text{Be}}$ and $^{8\text{B}}$ neutrino fluxes

Surface helium and convective radius

Sound speed data points
(from Basu et al, 2009)

And:

$$\begin{cases} U_Q & \text{Uncorrelated (observational) errors} \\ C_{Q,I} & \text{Correlated (systematical) uncertainties} \end{cases}$$

$$\{I\} = \{\text{opa}; \text{age}; \text{diffu}; \text{lum}; S_{11}, S_{33}, S_{34}, S_{17}, S_{e7}, S_{1,14}\}$$

A quantitative analysis of the solar composition problem

We take the **surface abundances** (with respect to hydrogen) as free parameters:

$$z_j \equiv Z_{j,b} / X_b$$

We group metals according to the method by which they are determined

$$1 + \delta z_{\text{CNO}} \equiv \frac{z_{\text{C}}}{\bar{z}_{\text{C}}} \equiv \frac{z_{\text{N}}}{\bar{z}_{\text{N}}} \equiv \frac{z_{\text{O}}}{\bar{z}_{\text{O}}} \quad (\text{photosphere})$$

$$1 + \delta z_{\text{Ne}} \equiv \frac{z_{\text{Ne}}}{\bar{z}_{\text{Ne}}} \quad (\text{chromosphere and corona})$$

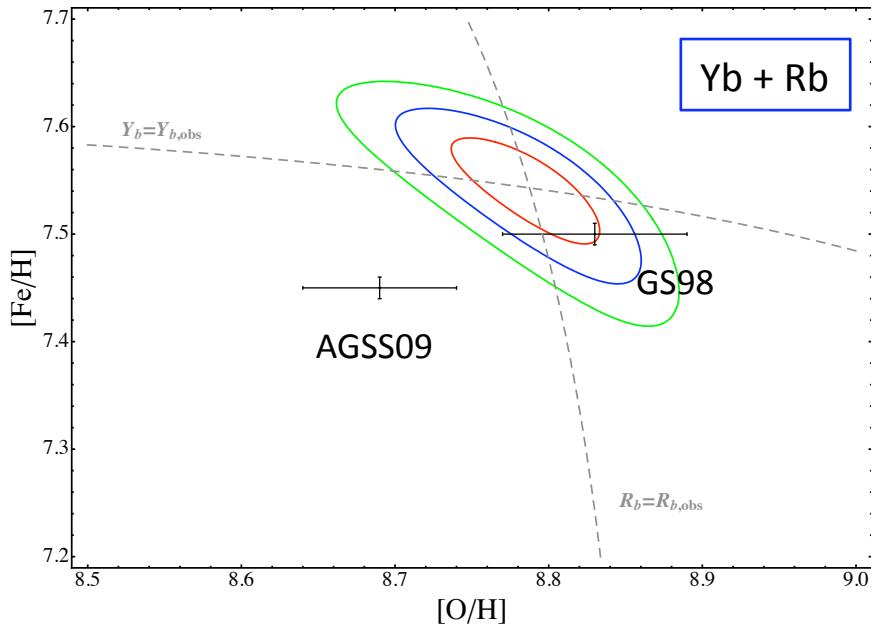
$$1 + \delta z_{\text{Heavy}} \equiv \frac{z_{\text{Mg}}}{\bar{z}_{\text{Mg}}} \equiv \frac{z_{\text{Si}}}{\bar{z}_{\text{Si}}} \equiv \frac{z_{\text{S}}}{\bar{z}_{\text{S}}} \equiv \frac{z_{\text{Fe}}}{\bar{z}_{\text{Fe}}} \quad (\text{meteorites})$$

We infer the **best-fit composition** by minimizing the χ^2 :

$$\chi^2 \equiv \chi_{\text{obs}}^2 + \chi_{\text{syst}}^2 = \sum_Q \tilde{X}_Q^2 + \sum_I \tilde{\xi}_I^2 \quad \dots \text{and the pull distribution can highlight tensions in SSM.}$$

$$\tilde{X}_Q \equiv \frac{\delta Q_{\text{obs}} - \sum_I \tilde{\xi}_I C_{Q,I}}{U_Q}$$

Two parameter analysis ($\delta z_{\text{CNO}} = \delta z_{\text{Ne}}$; δz_{Heavy})

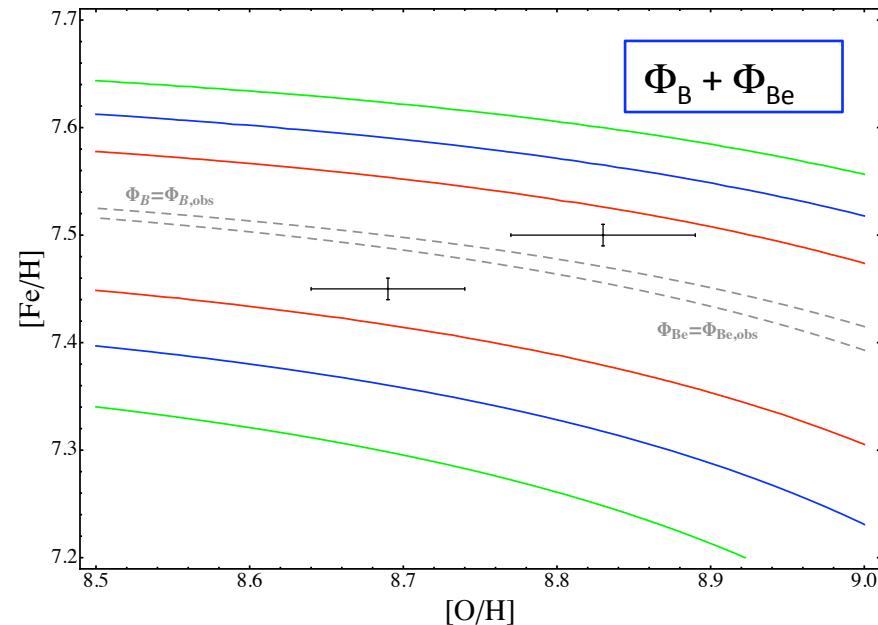
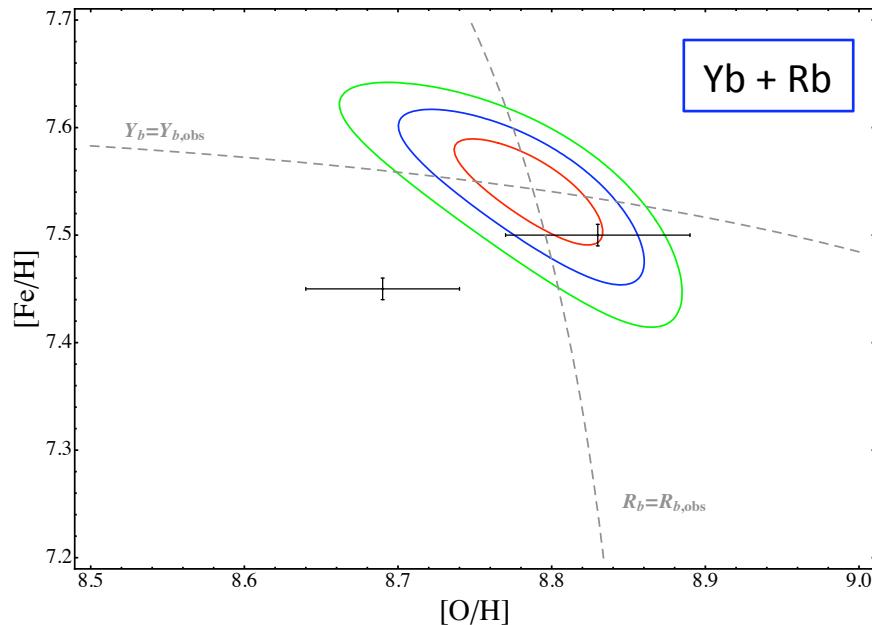


Astronomical scale for logarithmic abundances:

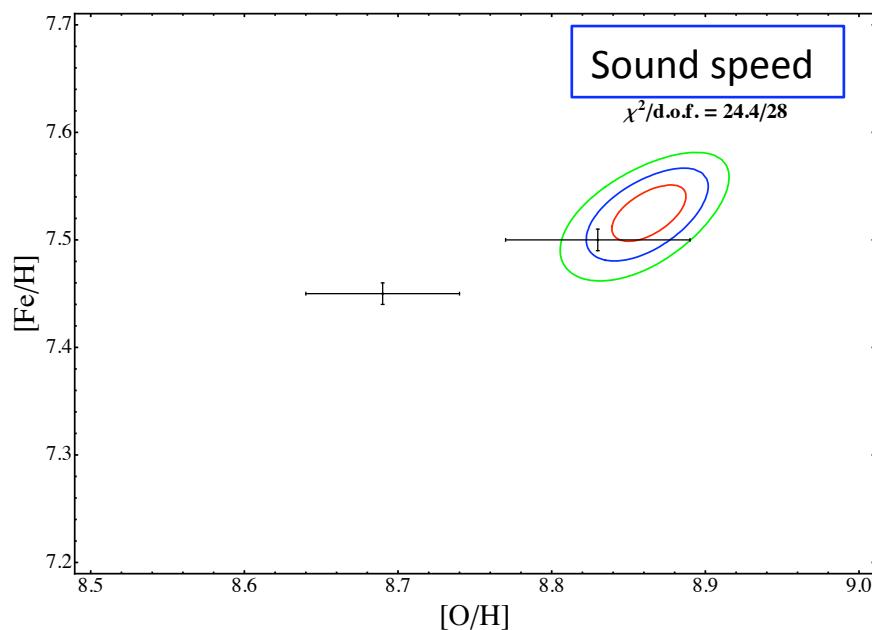
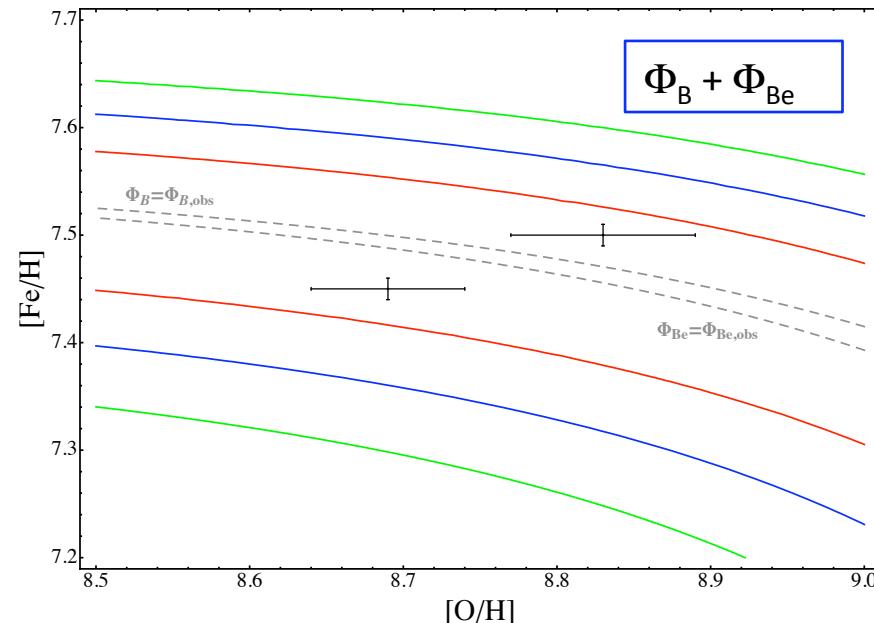
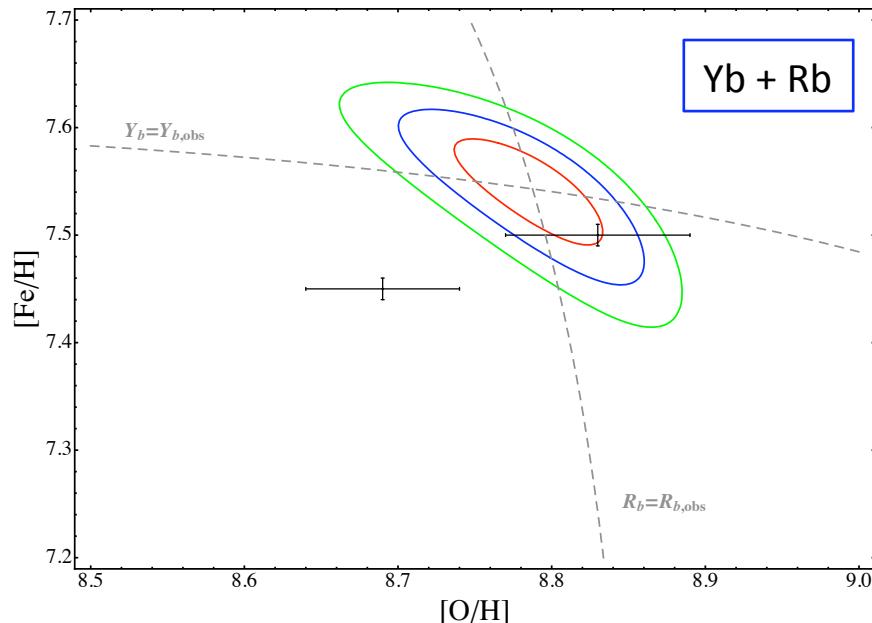
$$[I/\text{H}] \equiv \log (N_I/N_H) + 12$$

$$\begin{aligned} [\text{O}/\text{H}] &= \overline{[\text{O}/\text{H}]} + \log (1 + \delta z_{\text{CNO}}) \\ [\text{Fe}/\text{H}] &= \overline{[\text{Fe}/\text{H}]} + \log (1 + \delta z_{\text{Heavy}}) \end{aligned}$$

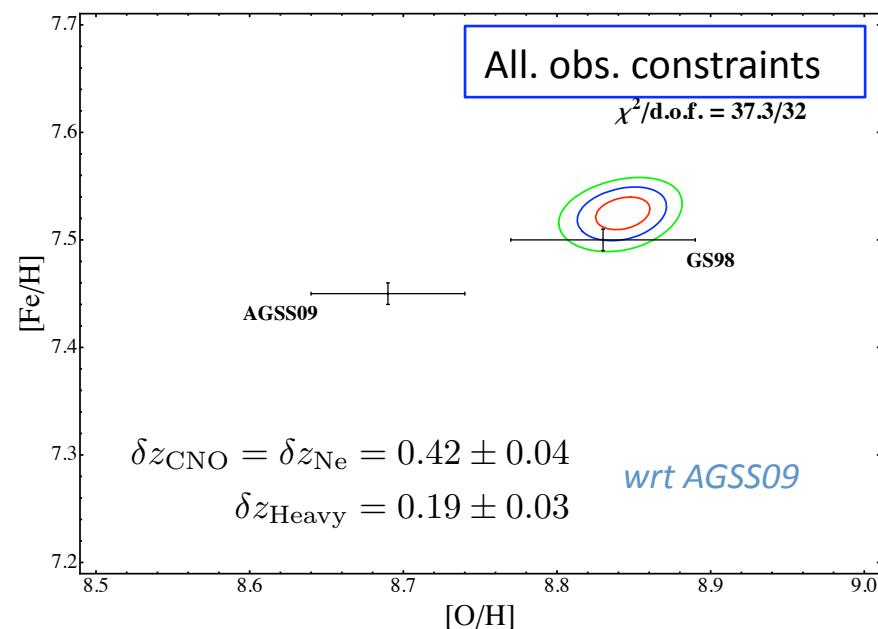
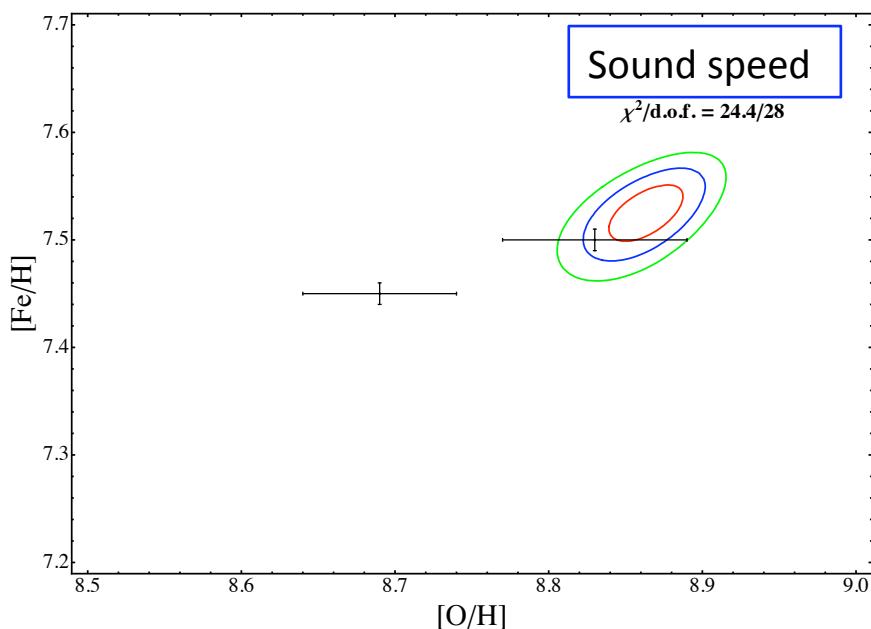
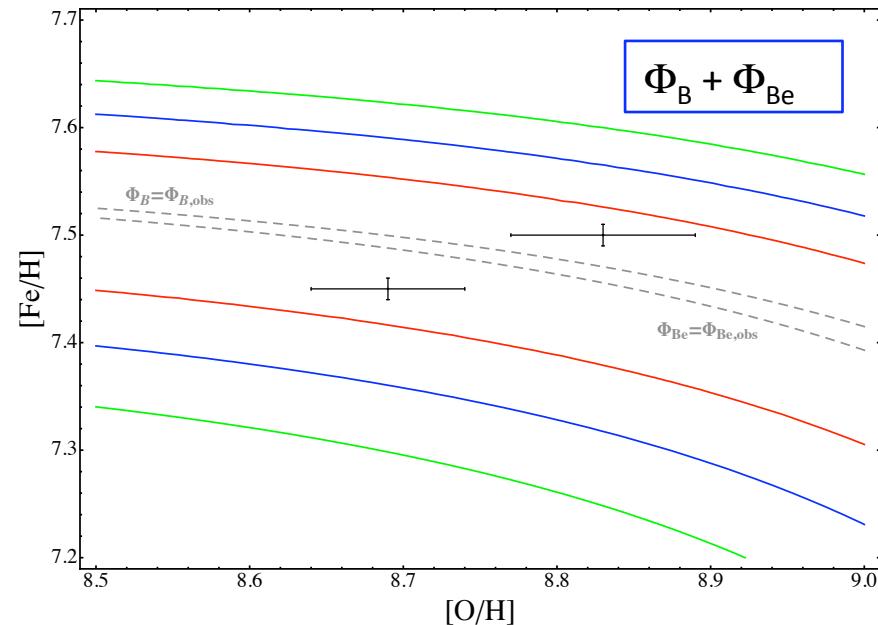
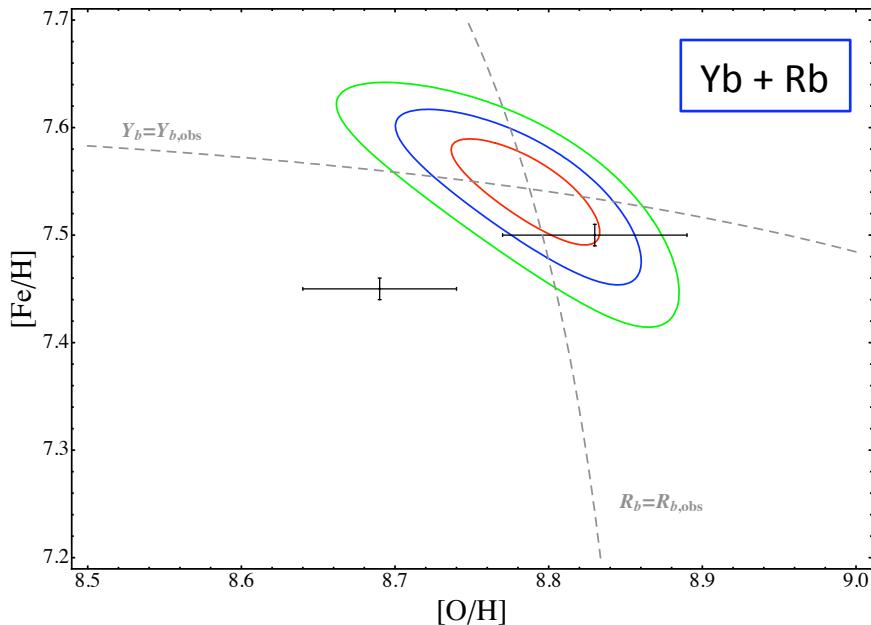
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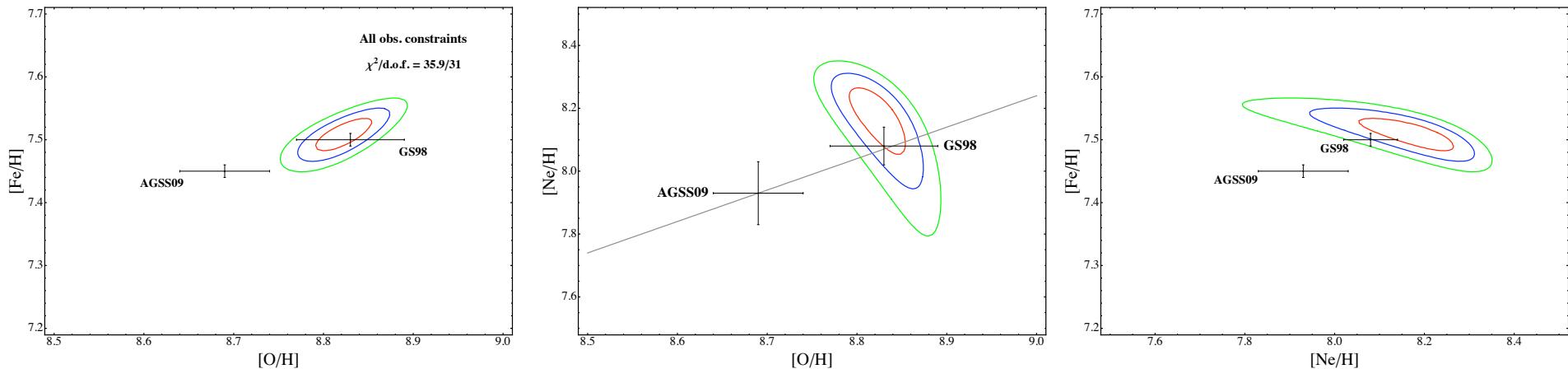


Two parameter analysis ($\delta Z_{\text{CNO}} = \delta Z_{\text{Ne}} ; \delta Z_{\text{Heavy}}$)

- ❖ The SSM implementing AGSS09 composition is **excluded** at an high confidence level being $\chi^2/\text{d.o.f.} = 176.7/32$.
- ❖ Substantial agreement between the infos provided by the various observational constraints. The quality of the fit is quite good being $\chi^2/\text{d.o.f.} = 37.3/32$.
- ❖ The best-fit abundances are **consistent** at 1 sigma with **GS98**.
- ❖ The **errors** on the inferred abundances **are smaller** than what is obtained by observational determinations.

Three parameter analysis (δZ_{CNO} ; δZ_{Ne} ; δZ_{Heavy})

Prior: Neon-to-oxygen ratio forced at the AGSS09 value with 30% accuracy

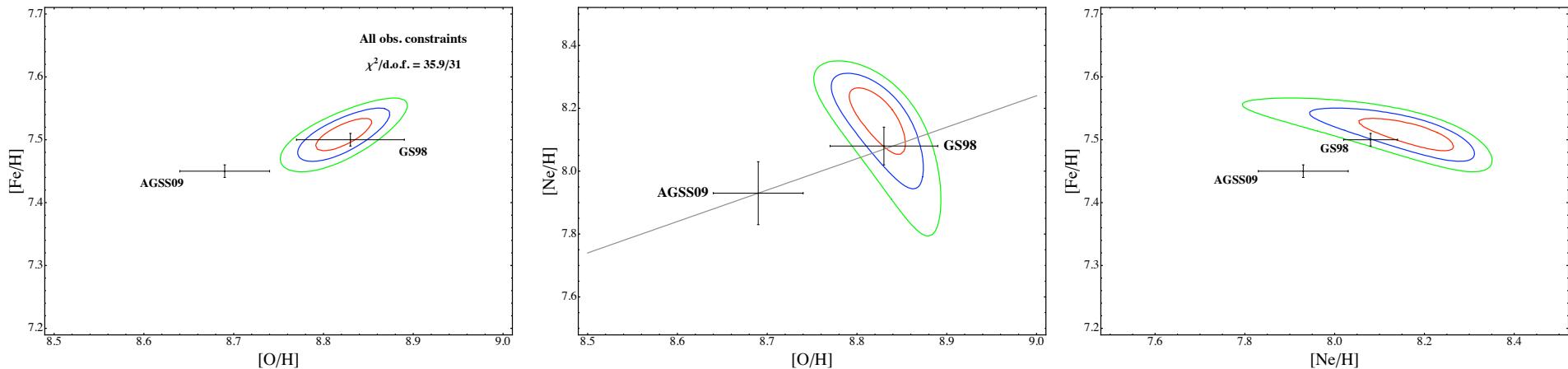


GS98 still favored by observational data but:

- errors in the inferred abundances larger than before;
- degeneracies appear among the various δZ_i ;
- obs.data do not effectively constrain the Ne/O ratio (we recover the prior).

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What data are really saying us? ...

Metals in the Sun

- Metals give a **substantial** contribution to **opacity**:

Energy producing region ($R < 0.3 R_o$)

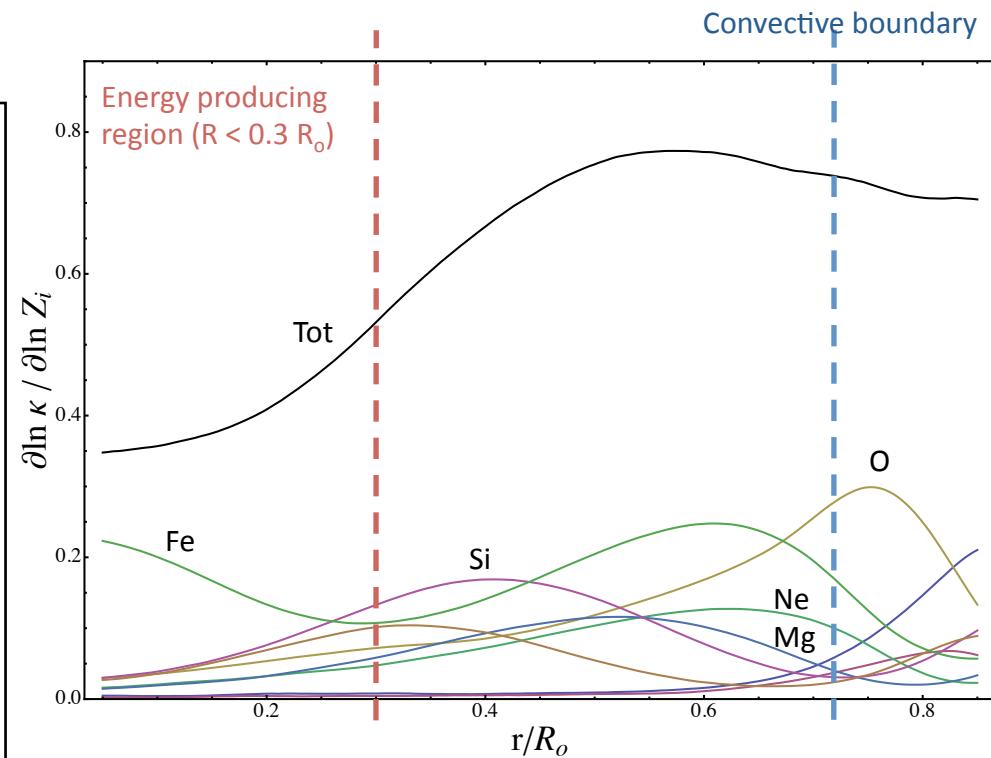
$$\kappa_Z \approx \frac{1}{2} \kappa_{tot}$$

Fe gives the largest contribution.

Outer radiative region
($0.3 < R < 0.73 R_o$)

$$\kappa_Z \sim 0.8 \kappa_{tot}$$

Relevant contributions from several diff. elements (O,Fe,Si,Ne,...)



Composition opacity change:

$$\delta \kappa_Z(r) \simeq \sum_j \frac{\partial \ln \kappa(r)}{\partial \ln Z_j} \delta z_j$$



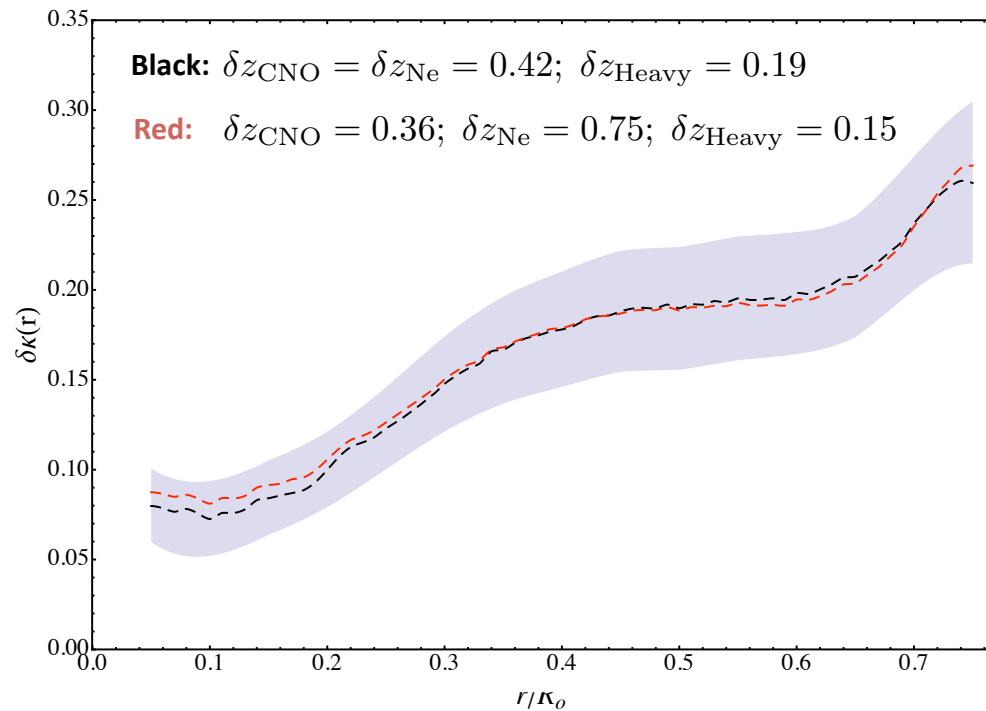
F.L. Villante and B. Ricci - *Astrophys.J.* 714:944-959, 2010

F.L. Villante – *Astrophys.J.* 724:98-110, 2010

What we know about the opacity profile of the present sun?

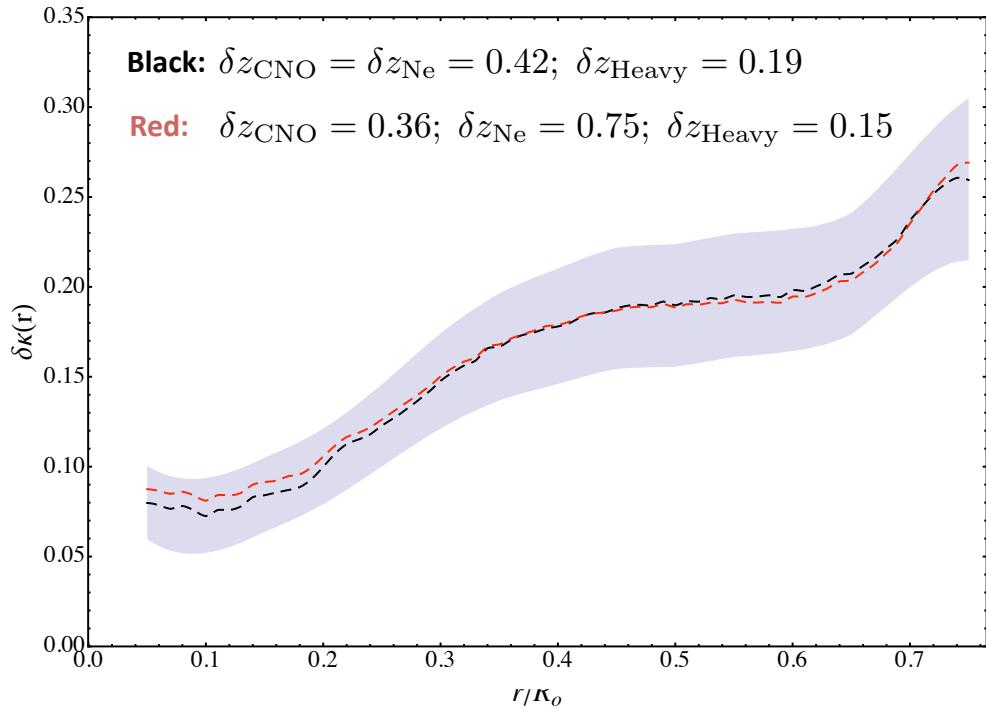
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Are there other effects that can provide the required opacity change?

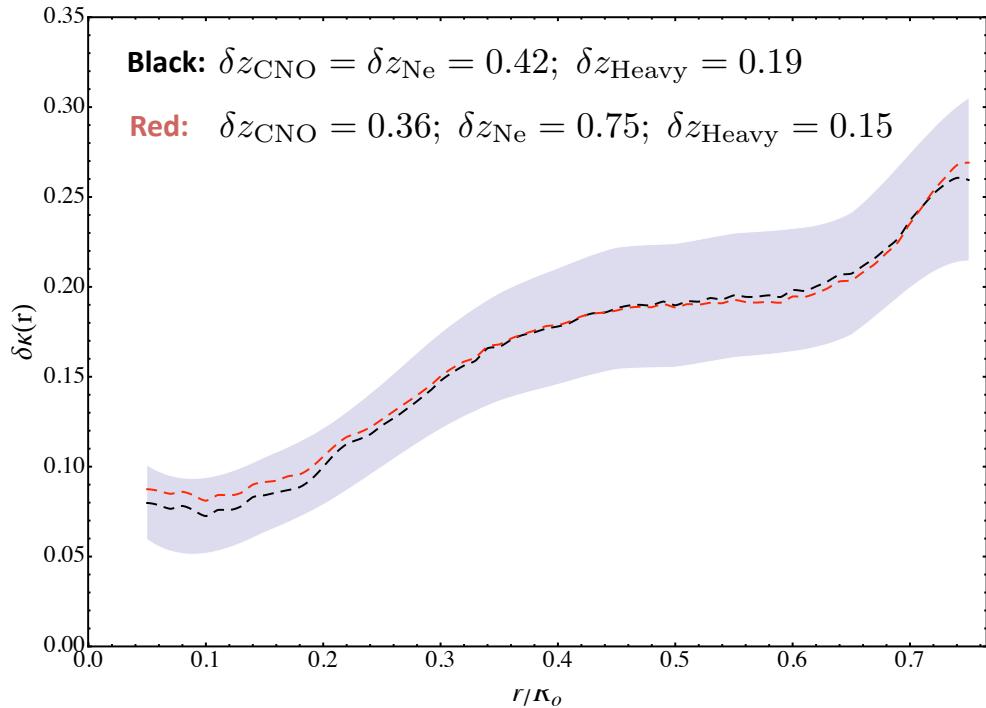
Wrong **opacity** calculations? → the required variations seems large wrt uncertainties

Different **distribution of metals** in the Sun? → According to the standard assumption, metals are nearly homogeneous in the sun (elemental diffusion is responsible for a slight increase at the solar center). Is this an oversimplified picture of chemical evolution?

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... Not just a problem of AGSS09.vs.GS98

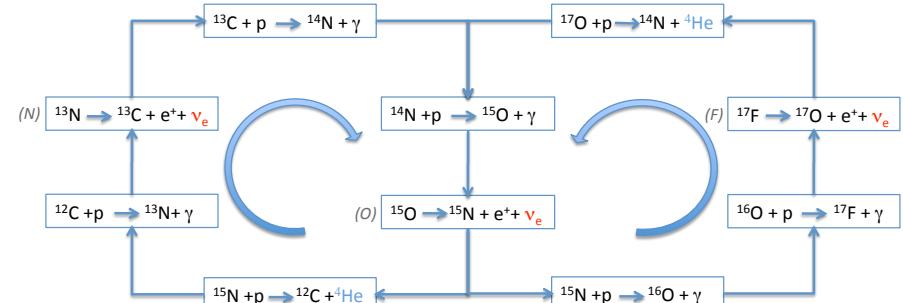
CNO neutrinos

CNO neutrinos break the degeneracy between opacity and metals:

$$1 + \delta\Phi_\nu = (1 + \delta X_{\text{CN}}) \left[1 + \int dr K_\nu(r) \delta\kappa(r) \right]$$

$$X_{\text{CN}} \equiv X_{\text{C}}/12 + X_{\text{N}}/14$$

Total number of catalysts for CN-cycle



Determines the central temperature

At present, we only have a loose upper limit on CNO neutrino fluxes:

ν flux	GS98	AGSS09	Solar
^{13}N ($10^8 \text{ cm}^{-2} \text{ s}^{-1}$)	$2.96(1 \pm 0.14)$	$2.17(1 \pm 0.14)$	≤ 6.7
^{15}O ($10^8 \text{ cm}^{-2} \text{ s}^{-1}$)	$2.23(1 \pm 0.15)$	$1.56(1 \pm 0.15)$	≤ 3.3
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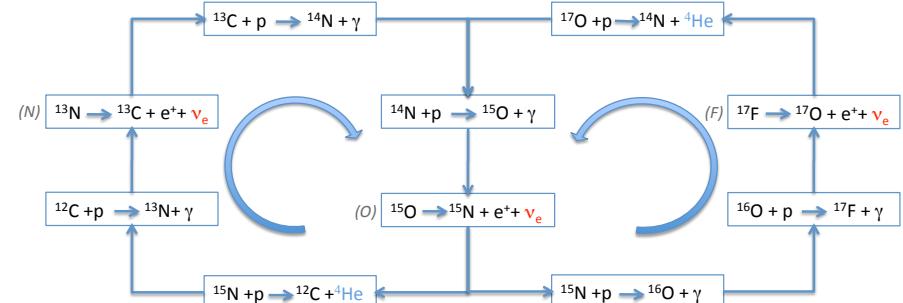
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Will it be possible to detect CNO neutrino?

*Very difficult, in practice. Not impossible, in principle
(ask if you are interested)*

Summary and conclusions

- ◆ The **solar composition** problem is still open and is potentially pointing at inadequacy in standard solar model paradigm.
- ◆ The opacity changes required to fit **helioseismic and solar neutrino** data seem large with respect to current opacity and composition uncertainties;
- ◆ Hopefully, **future neutrino flux** measurements (Be, **CNO**, pep) will provide additional clues for the solar composition puzzle.

Bibliography

- The solar composition problem: a quantitative analysis

F.L. Villante et al. – In preparation

- Linear Solar Models: a tool to investigate the solar interior

F.L. Villante and B. Ricci - Astrophys.J.714:944-959,2010

F.L. Villante - J.Phys.Conf.Ser.203:012084,2010

- Application: what we know about opacity and metals in the sun

F.L. Villante – Astrophys.J.724:98-110,2010

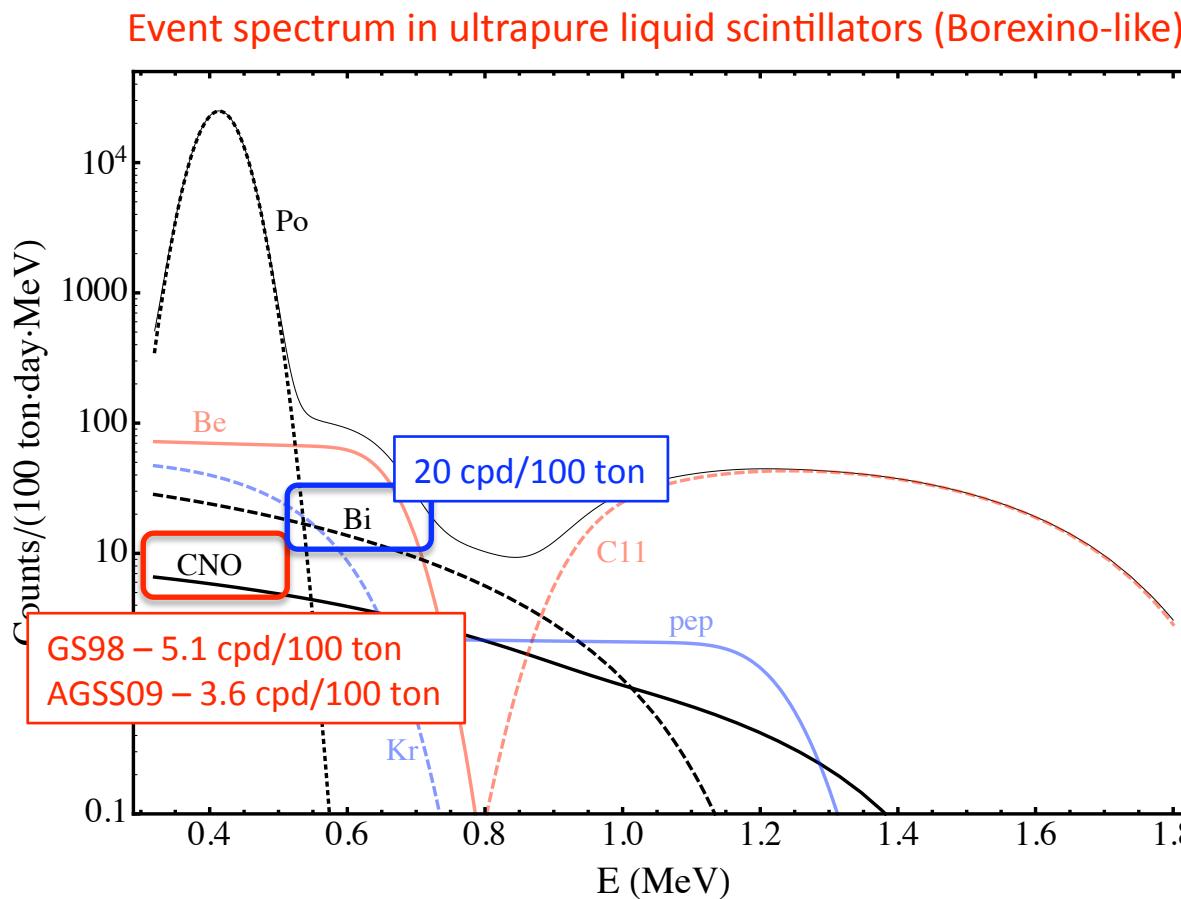
- A step toward CNO neutrino detection

F.L. Villante et al. - Phys.Lett. B701 (2011) 336-341

Is it possible to observe CNO neutrinos?

The detection of CNO neutrinos is very difficult:

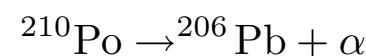
- Low energy neutrinos → endpoint at about 1.5 MeV
- Continuous spectra → do not produce recognizable features in the data.
- Limited by the background produced by beta decay of ^{210}Bi .



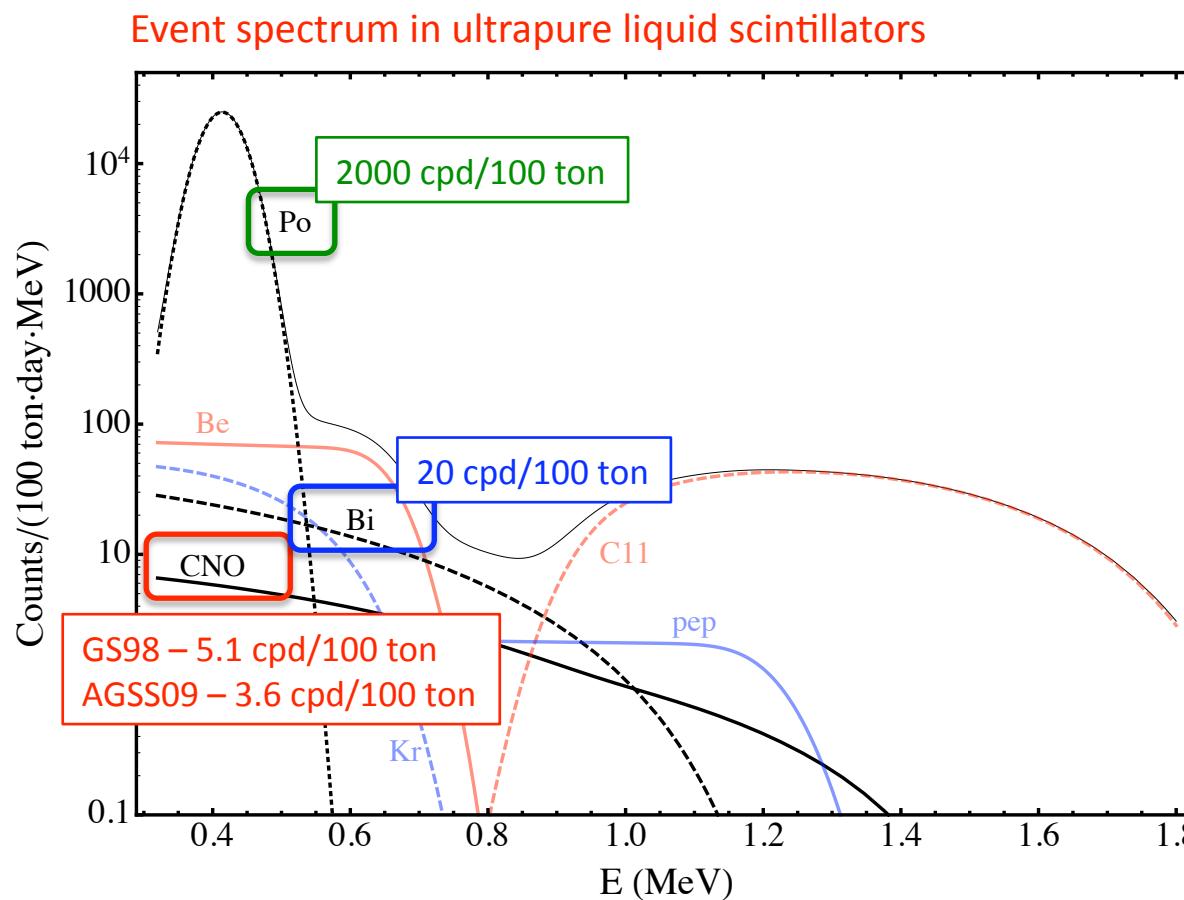
Determining ^{210}Bi with the help of ^{210}Po ?



$$\tau_{\text{Bi}} = 7.232 \text{ d}$$



$$\tau_{\text{Po}} = 199.634 \text{ d}$$



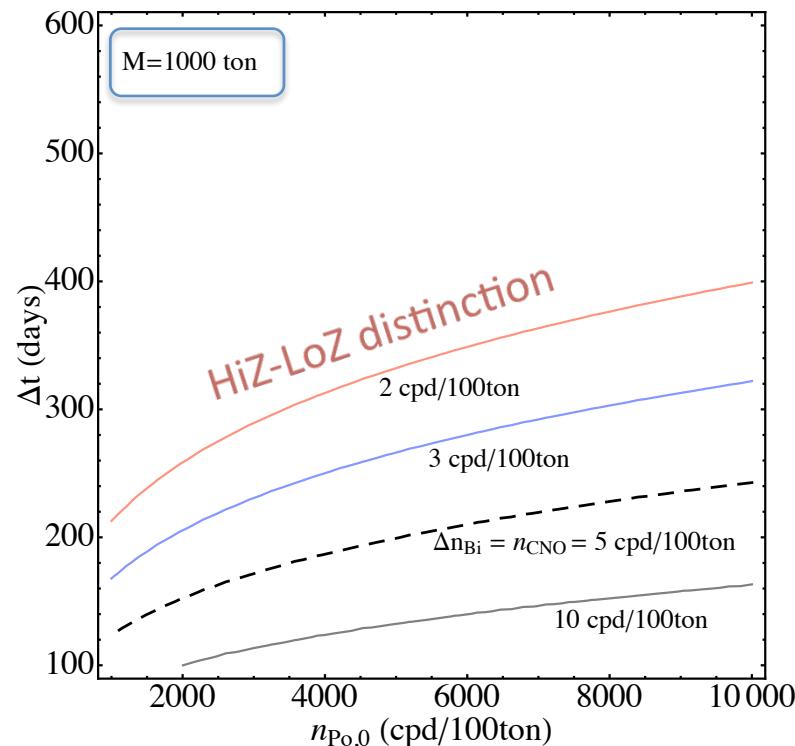
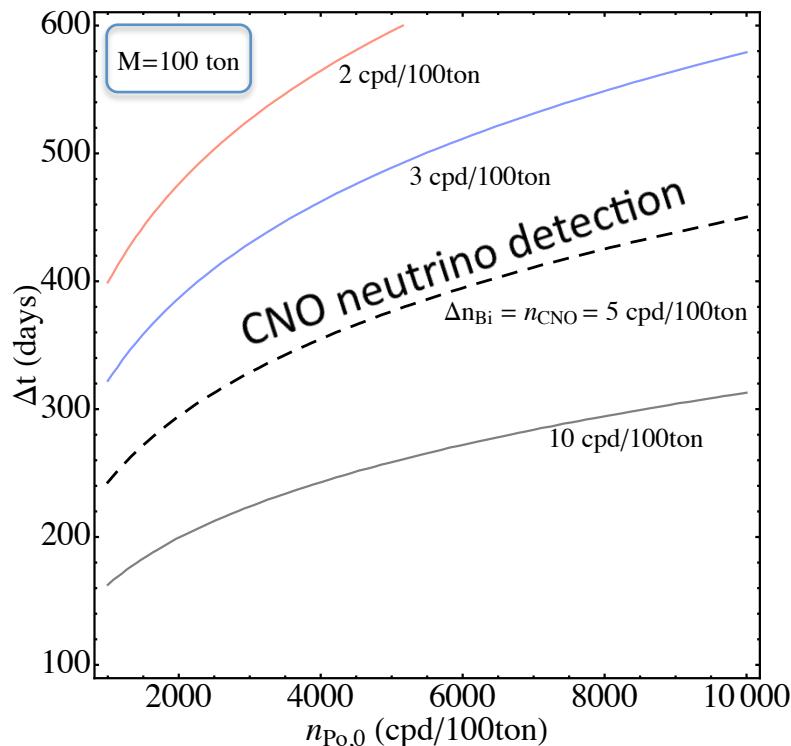
Deviations from the exponential decay law of Po210 can be used to determine Bi210:

$$n_{\text{Po}}(t) = [n_{\text{Po},0} - n_{\text{Bi}}] \exp(-t/\tau_{\text{Po}}) + n_{\text{Bi}}$$

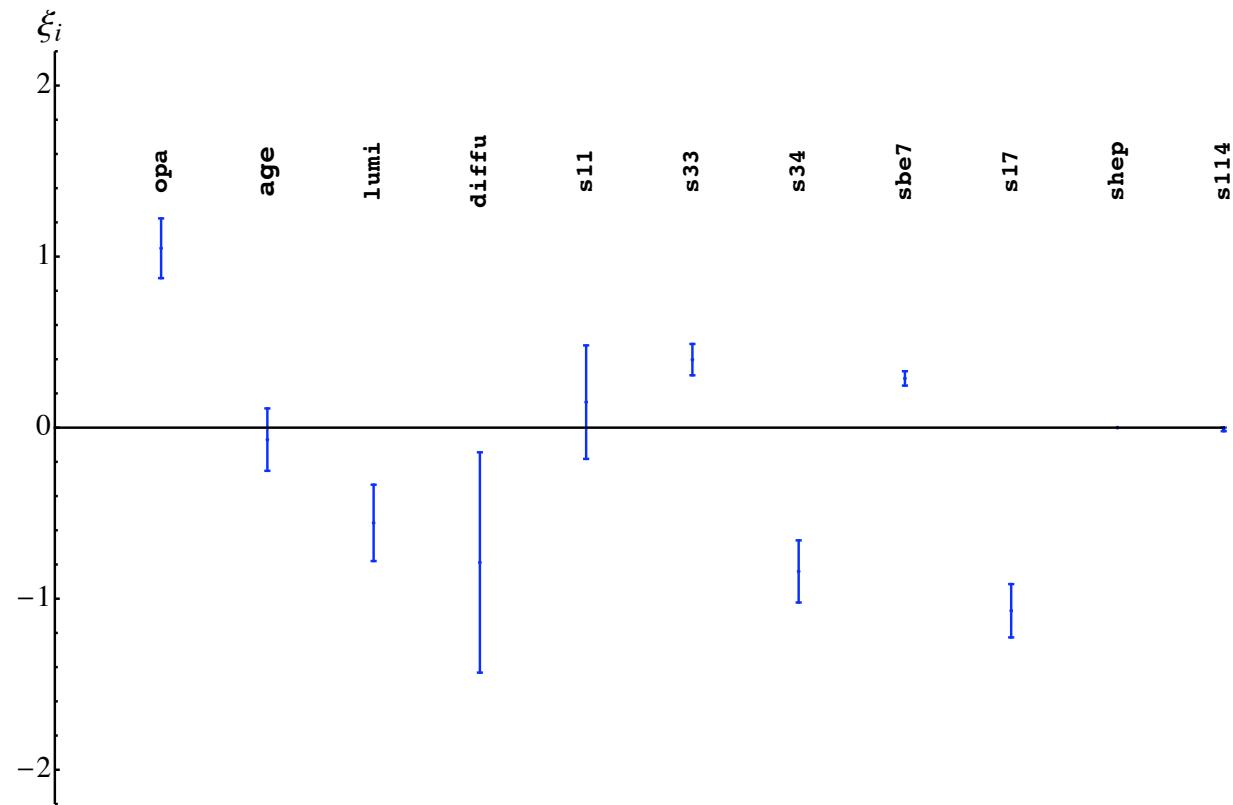
Expected accuracy:

$$\Delta n_{\text{Bi}} \simeq \sqrt{\frac{n_{\text{Po},0}}{\tau_{\text{Po}} M}} f(\Delta t)$$

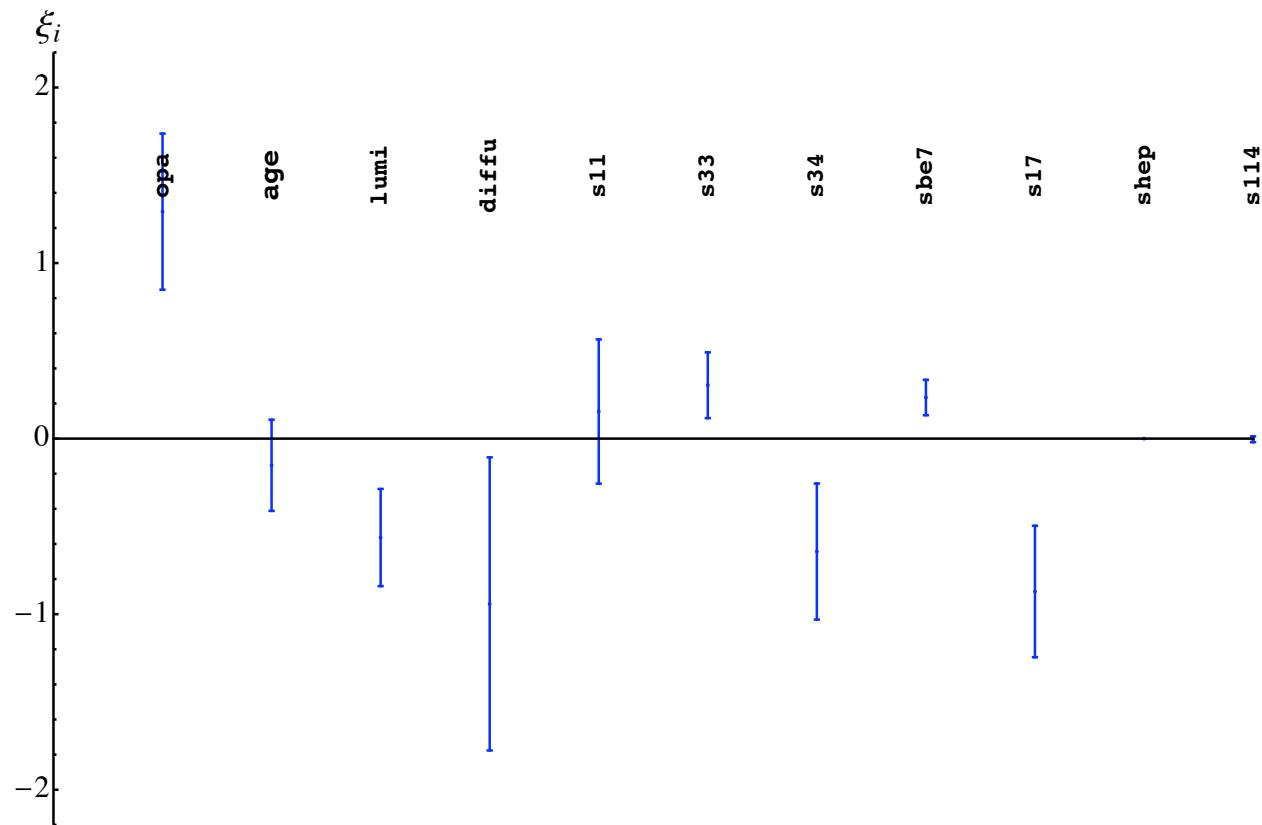
$$f(\Delta t) = \left(\frac{2 \tau_{\text{Po}}}{\Delta t} \right) e^{-\frac{\Delta t}{4 \tau_{\text{Po}}}} \sqrt{\frac{1 + e^{-\frac{\Delta t}{2 \tau_{\text{Po}}}}}{1 - e^{-\frac{\Delta t}{2 \tau_{\text{Po}}}}}}$$



Pulls of systematics – 2 parameter analysis



Pulls of systematics – 3 parameter analysis



The theoretical error budget

	Age	Diffu	Lum	S_{11}	S_{33}	S_{34}	S_{17}	S_{e7}	$S_{1,14}$	Θ_{pa}
Y_b	-0.001	-0.012	0.002	0.001	0	0.001	0	0	0.	0.0036
R_b	-0.0004	-0.0029	-0.0001	-0.0006	0.0001	-0.0002	0	0	0	0.0014
Φ_{pp}	0	-0.002	0.003	0.001	0.002	-0.003	0	0	0	-0.0008
Φ_{Be}	0.003	0.022	0.014	-0.010	-0.023	0.047	0	0	0	0.009
Φ_B	0.006	0.044	0.029	-0.025	-0.022	0.046	0.075	-0.02	0	0.020
Φ_N	0.004	0.054	0.018	-0.019	0.001	-0.003	0	0	0.051	0.013
Φ_O	0.006	0.062	0.024	-0.027	0.001	-0.002	0	0	0.072	0.018

Table 1: *The contributions $C_{Q,I}$ to uncertainties in theoretical predictions for helioseismic observables and solar neutrino fluxes.*